# eRD22 GEM-TRD/T R&D Progress Report

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June 27, 2018

**Project ID:** eRD22
**Project Name** GEM based Transition radiation detector and tracker
**Period Reported:** from 07/2017 to 07/2018
**Project Leader:** Yulia Furletova
**Contact Person:** Yulia Furletova

**Abstract**

Transition radiation detectors are widely used for electron identification in various particle physics experiments. For a high luminosity electron-ion collider a high granularity tracker combined with a transition radiation option for particle identification could provide additional electron identification/hadron suppression. Due to the low material budget and cost of GEM detector technologies, a GEM based transition radiation detector/tracker (GEM/TRD/T) is an ideal candidate for large area hadron endcap where a high flux of hadrons is expected at EIC.

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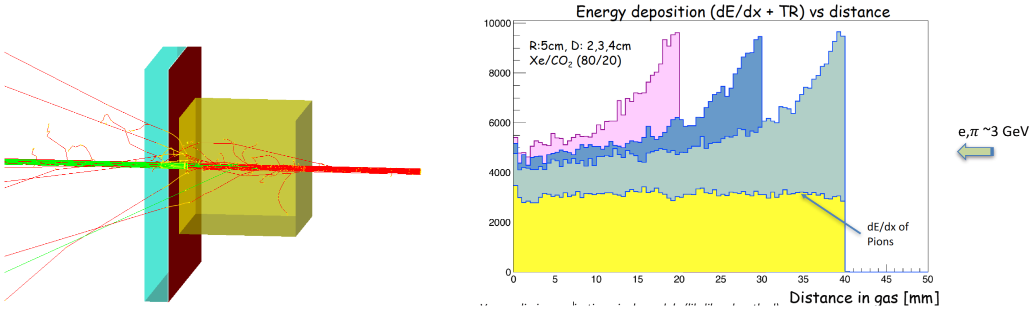



Figure 1: Geant4 simulation of TRD setup(left) and energy deposition vs drift distance (right)

# 1 Introduction

Identification of secondary electrons plays a very important role for physics at the Electron-Ion Collider(EIC). J/$\psi$ has a significant branching ratio for decays into leptons (the branching ratio to electrons ($e^+e^-$ pair) is similar to muons ($\mu^+\mu^-$ pair) and is the order of 6%). The branching ratio of D-mesons is Br($D^+ \to e + X$) $\sim$ 16% and the branching ratio of B-mesons is Br($B^\pm \to e + \nu + X_c$ ) $\sim$ 10%. By using more sophisticated electron identification the overall J/$\psi$ and open charm or beauty mesons efficiency could be increased and therefore statistical uncertainties could be improved. Electron identification is also important for many other physics topics, such as spectroscopy, beyond the standard model physics, etc. A high granularity tracker combined with a transition radiation option for particle identification could provide additional information necessary for electron identification or hadron suppression.

The scope of this project is to develop a transition radiation detector/tracker capable of providing additional pion rejection (>10-100).

# 2 PAST

- *What was planned for this period?*
  This is a first year of the eRD22 project. The advisory committee recommended focusing on a GEANT4 simulation of the GEM/TRD setup in the first stage of the project. Our goals were to simulate a GEM-TRD setup, build a first prototype and perform the first test-beam measurements, which would allow us to compare a simulation and a real response of the detector for an electron identification.

- *What was achieved?*

## 2.1 GEANT4 simulation

We performed a GEANT4 simulation and optimized the radiator and detector thicknesses for a single chamber (Fig. 1), described in the previous report in more detail. During this half of the year we focused on a calculation of e/$\pi$ rejection factor using simulated data, as well as preparing a setup for an extraction of e/$\pi$ rejection using real data. During the current test beam we had only an electron beam, therefore we compared only the electron response of the detector. This was done using two configurations: with radiator and without radiator, where response of the detector without TR-radiator would "mimic" a pion response. From now on under e/$\pi$ rejection factor we consider $e_{with}/e_{without}$ TR-radiator. (Note, that average dE/dx for pions is lower then for electrons, therefore $e/\pi$ rejection factor will be better than $e_{with}/e_{without}$.)

For e/$pi$ rejection factor we analyzed the amplitude and arrival time of each individual cluster along the drift time. We also calculated the total number of clusters and number of clusters within sub-segments ( the total drift volume was subdivided into 20 slices(Fig. 2). This allowed us to study the number of clusters as well as the average energy loss withing a sub-segment of the drift volume. Typical clusters are shown on Fig. 13.

All this information (ca. 30 variables) was used as input for likelihood or an artificial neural network (ANN) program (JETNET). The ANN system as trained with MC samples of incident electron and pions, and then independent sample was used to evaluate a performance. Example of such training procedure is shown on Fig. 3. Ca. 50 epochs (or training circles) are required to achieve necessary performance of a NN system. We require a 90% efficiency for our electron identification. As a result, we achieved a rejection factor of 2.4 (4.5) with a 2cm (4cm) of Xe and 10cm of radiator(fleece). For 70% electron efficiency a rejection factor of 12 (17) could be achieved for 2cm (4cm) of Xe and 10cm of radiator.

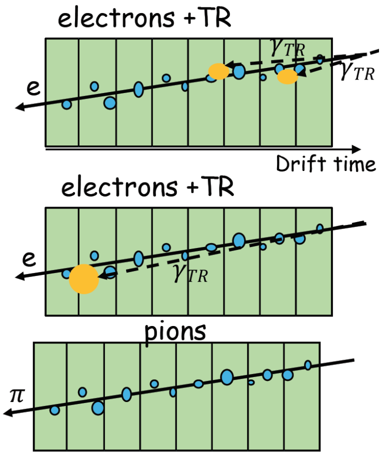



Figure 2: Shematic view of regions along the drift time used for e/$pi$ identification

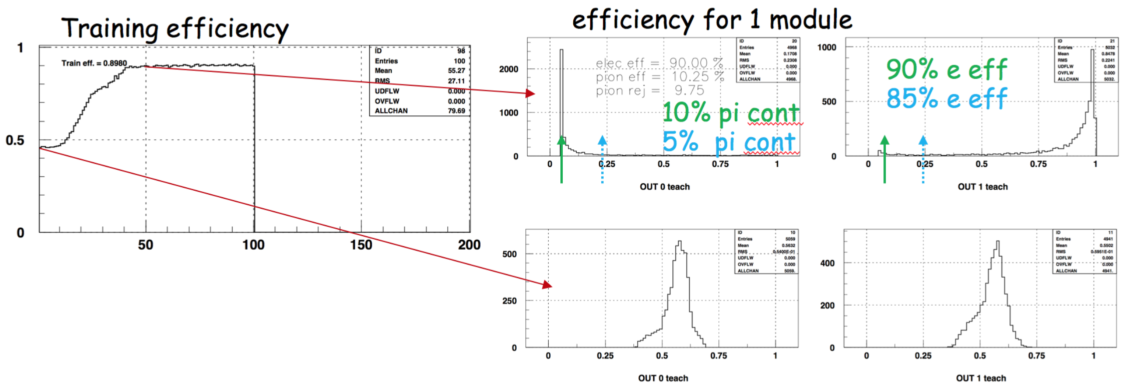



Figure 3: Example of calculation an efficiency and rejection factor using the artificial neural network (ANN). Number of training epochs(left) and ANN output value before and after training (right plots)

## 2.2 Prototype

The eRD22 GEM-TRD/T proto I was built with an improved design from the beta version that was assembled and tested as a proof of principle in Spring 2017. The current prototype (proto I) has implemented a number of modifications (listed below) to minimize the material at the entrance window and optimize the drift field in the drift region of the detector.

### 2.2.1 Modification of the entrance gas window design

For GEM-TRD/T proto I, the gas box has been modified to minimize the gap between the entrance window foil and the drift cathode foil to less than 400 $\mu$m (compared to 4 mm for beta-proto). This is a critical change as it drastically reduces the number of x-ray photons to be converted in this dead area of the detector in Xe-CO2 gas mixture and therefore increases the detection efficiency of the TRD detector. The gas box has also been modified to eliminated the gas leaks that we

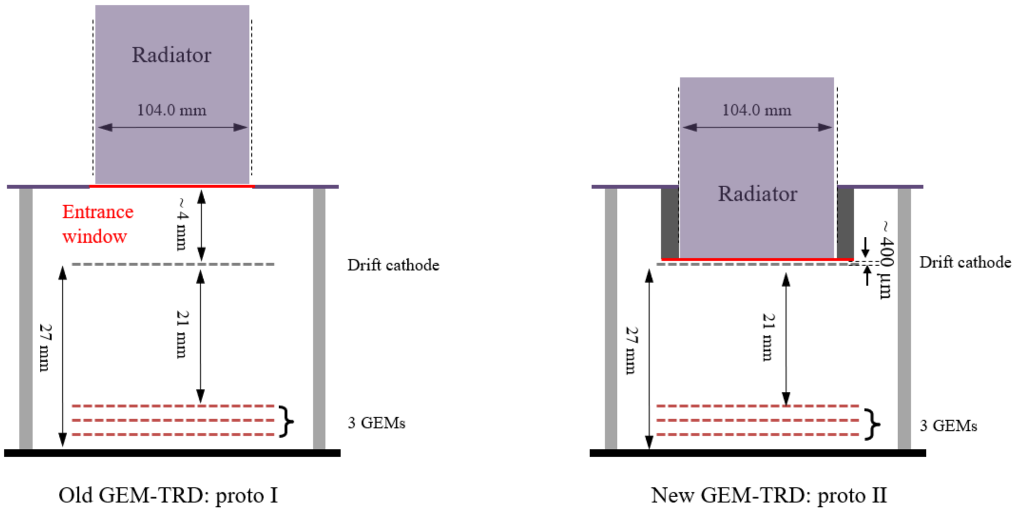



Figure 4: Cross section of the detector design: beta-proto with 4 mm gas entrance window (left); proto I with 0.4 mm gas entrance window.

experienced with the beta-proto which was not design for a TRD application. Fig. 4 shows a cross section of the detector design and the improvement from beta-prototype to the current prototype-I.

#### 2.2.2 Modification of the drift cathode and entrance window foils

The drift cathode was modified from the previous prototype by replacing the 5 um Cu layer on a 50 um Kapton foil with an ultra-thin (0.2 um) Chromium (Cr) layer. This replacement of the Cu by an ultra-thin Cr will also significantly improve the detection efficiency of the TRD photons by reducing the photon conversion inside the drift cathode itself. A picture of the Cr-cathode is shown on the left in Fig. 5. For the entrance window, we use 25 $\mu$m Kapton foil.

#### 2.2.3 Re-design of the 2D strip readout board

The readout board of the standard CERN triple-GEM design is also the anode layer where the electrode contacts (pads) for voltage distribution through the various layers of the detector are made. In the TRD configuration, in addition to the standard 7 electrodes needed to supply voltage to the GEM foils, 6 additional electrode contacts were needed in order to supply voltage to the 21 mm field cage. The 2D X-Y strips readout board was modified accordingly to accommodate the additional HV electrodes. The picture on the right of Fig. 5 shows the stack of the drift cathode and 3 GEM foils with the connection to the HV pads on top of the modified readout board.

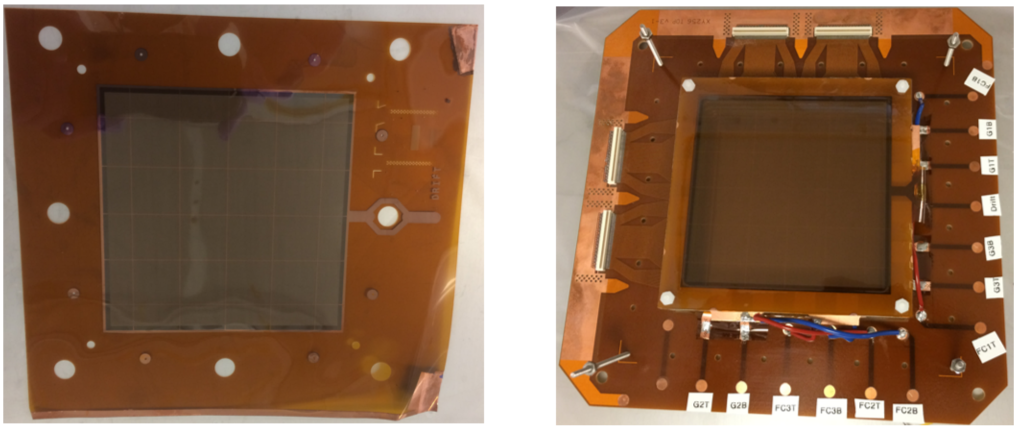
### 2.3 HV divider

We redesigned a voltage divider in order to separate drift voltages from amplification voltages. That allowed us to perform a scan and optimization of drift and amplification voltages independent from each other. Additional filtering was used to improve/reduce a noise of the detector.

### 2.4 Readout electronics

As we learned, a standard APV25 readout chip is not capable of covering a full drift range of a GEM-TRD, as well as it has a limited timing resolution (25ns/bin, with a peaking time of 50ns, and total range of maximum 600ns). Therefore we developed and fabricated a new interface board, which is compatible with an existing JLAB Flash-ADC readout. FADC125 have a timing resolution of 8ns/bin and covers a whole drift time range $>1\mu s$. We used 4 FADC125 boards, with 72 channels each, which allowed us to cover all X-strips of the GEM detector but only some of the Y-strips. All the DAQ components used for the test were borrowed from JLAB (Hall-D).

We used interface boards (one per each x/y coordinate), see Fig. 7, which holds 10 pre-amplifiers. Each pre-amplifier connects to 24 GEM strips, resulting on a readout of 240 GEM strips per each readout board or X/Y coordinate.



Cr drift cathode foil

Drift cathode and GEM stack
on new R/O board

Figure 5: Drift cathode with 200 nm Cr layer (left). Stack of Cr-cathode and 3 GEMs on of the new readout board.

A pre-amplifier has GAS-II ASIC chips (3 chips per each pre-amplifier card) and provides 2.6 mV/fC amplification. A pre-amplifier has a peaking time of 10 ns. It consumes 50 mWatt/channel and has a noise <0.3 fC. The dynamic range of pre-amplifiers (where it is linear) is about 200 fC.

## 2.5 Gas system

The GEM based TRD R&D is currently in the early stages and is still being developed as a proof of principle detector. As such, there is not enough funding available at this time to build a full-fledged gas system which includes a gas mixer, circulation pumps, gas purifiers, and analyzers. Thus, it was decided to focus some of the available funding on the gas mixing system. This system will allow us to mix custom concentrations of Xe/CO2 gas, which is the ideal detector gas for TRD detectors. Figures 8 and 9 show the design of the Xe/CO2 gas mixing system. Figure 8 details the gas configuration panel, which determines what gases will be mixed, while Fig. 9 shows the gas mixing control panel. The *to detector* line would then connect up to the current detector gas system. The main components of the gas mixing system are the two mass flow controllers from Teledyne Hastings (HFC-302B). The mass flow controllers were purchased under the assumption of a nominal gas flow of 50 SCCM and concentration of 70 (Xe)/30 (CO2), however dynamic ranges of the flow controllers were selected to add flexibility in the gas concentrations. The mass flow controllers will need to be calibrated for each gas type and each flow rate. To do this will have built a simple apparatus (Fig. 10, left panel) which allows us to track the volume displaced during a given time duration. This apparatus is based on the same calibration device/process that is currently being used in the BNL lab for their mass flow calibrations. The measurement is carried out by filling an inverted graduated cylinder with water and then releasing the gas to be calibrated into the graduated cylinder. The flow rate can then be calculated by the ratio of the volume change to time duration. As of this writing the gas mixing system has now been fully assembled (Fig. 10, right panel) and is beginning leak testing. This will then be followed by the implementation of the mass flow controller-computer interface and then the calibration of the following gas types for a 50 ccm flow rate: N2, Ar, CO2, Xe.

## 2.6 Test beam setup

We used 3-6 GeV electrons coming from the pair spectrometer (Fig. 11 right) in parallel with a setup of multi-wire TRDs (MW-TRD or FDC). A 10 cm fleece radiator was placed in front of the GEM entrance window. We used a ZEUS-TRD radiator material, which consists of polypropylene (PP) fibers of diameter 20$\mu$m and with a random fiber orientation (material density is 0.083g/$cm^3$, or $\sim 1.5\% X_0$ for 10 cm of radiator), as a default/standard radiator.

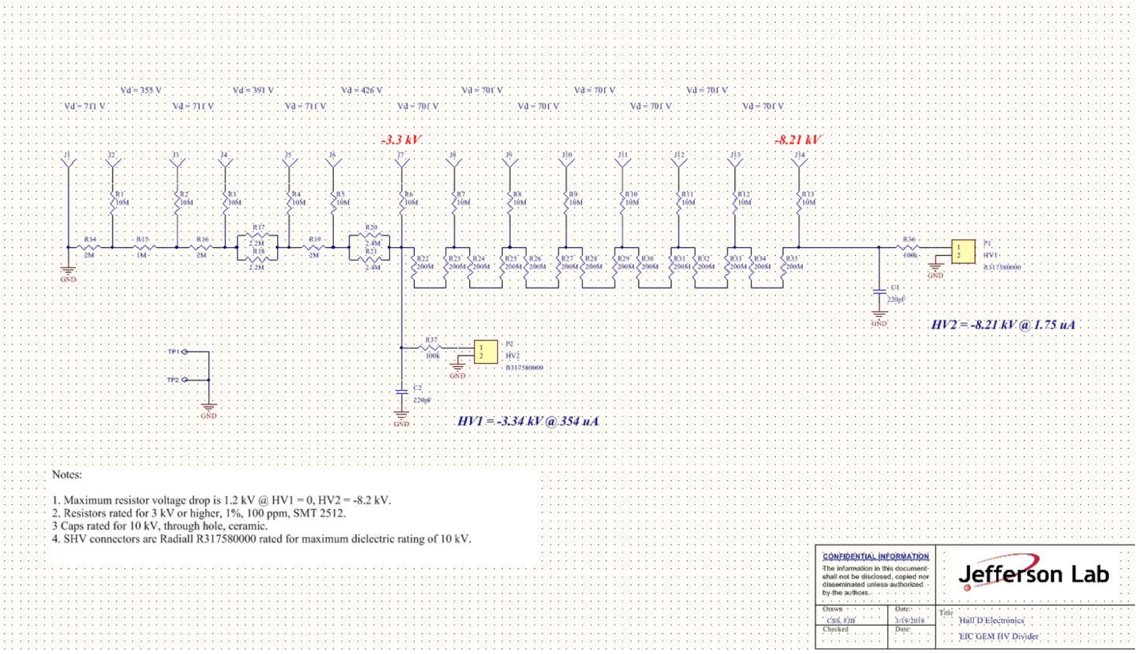



Figure 6: A schematic of a HV divider

## 2.7 First test beam results

We performed the first measurements of GEM-TRD/T prototype with Xe gas mixture. A comparison of the detector responses with and without radiator is shown on /reffig:FirstXe left plot (red and blue lines respectively). The very first results (Fig. 12, left plot) showed a slope (or lose-of-charge or non-uniformity) in a distribution of charge along the drift volume (blue line on Fig. 12) for particles passing the area without radiator. But one could clearly see an increase of a charge coming from TR-photons(red curve) especially in the area close to the entrance window (larger drift-time). This slope might be explained by the following reasons: diffusion of clusters, leakage in a gas system ( bad gas mixture) leading to electron recombination or a space charge effect.

Different thresholds applied to dE/dx clusters showed no change in the slope, proving that there are no effects of diffusion (Fig. 12,right plot), where red and blue dots correspond to different cluster thresholds. Since we do not have a purification system or a gas analysis system, the gas flow was increased to remove the gas effects. The slope in dE/dx distribution (Fig. 12,right plot) could be explained by a presence of contaminations in the gas. Without a gas analyzer we were not able to estimate levels or sources of gas contaminations (we added a request for a purchasing a gas analyzer for FY19).

On Fig. 13 the typical signals from GEM-TRD prototype processed using FlashADC125 are shown.

### 2.7.1 Tracking

We simultaneously tested both a GEM-TRD and a MultiWire-TRD (MW-TRD or FDC) prototype, which allowed us to compare the response of both chambers on an event by event basis. Fig. 14 shows three event displays (3 columns) with the MW response in the upper row and the GEMTRD response in the lower row. As one can see the individual clusters along the particle track are more "pronounced" in the GEM-TRD prototype.

### 2.7.2 Different radiators

We performed a test with different radiators. We used ZEUS-TRD radiator material (PP fibers with a random fiber orientation, and material density of 0.083g/cm3) (Fig. 15 left plot). We also performed a test with a regular structure radiator which had ca. 200 13$\mu$m Mylar foils separated

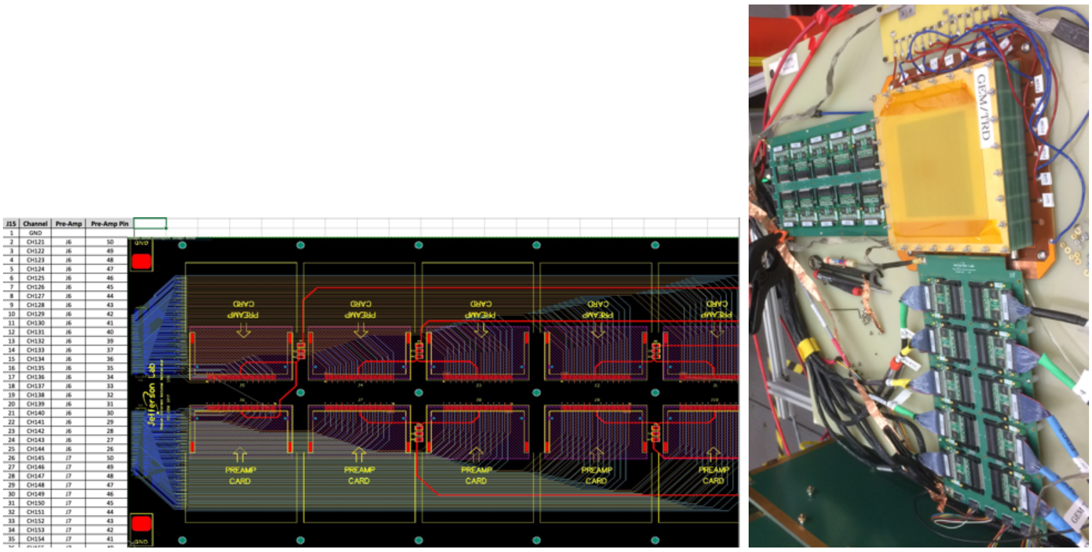



Figure 7: Readout boards with pre-amplifiers.

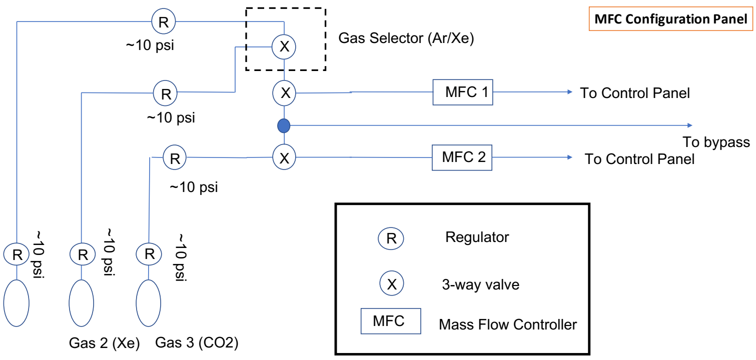



Figure 8: Gas mixer configuration panel design.

by 180$\mu$m spacers made from nylon net. The performance of our system with this type of radiator is shown on Fig. 15 (right).

### 2.7.3 Different HV settings

We made a drift field scan to optimize a performance of GEM/TRD/T. This scan would allow us to compare a real detector performance with a simulation predictions from GARFIELD/MAGBOLTZ. The preliminary results are shown on Fig 16.

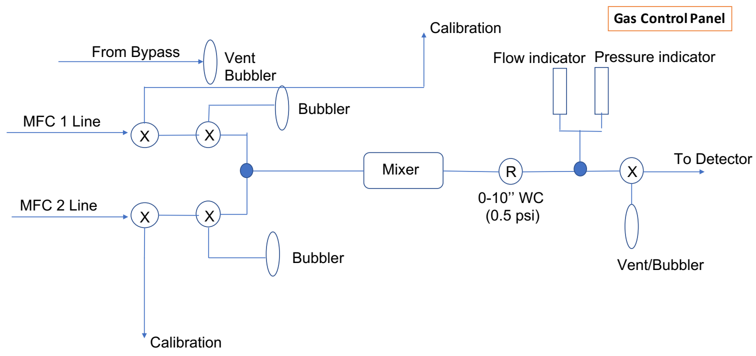



Figure 9: Gas mixer control panel design.

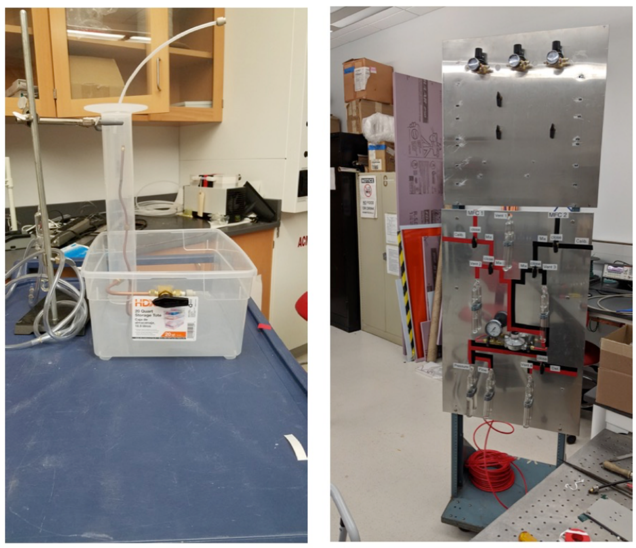


Figure 10: Mass flow rate calibration apparatus (left) and assembled (gas sources still need to be connected) gas mixer configuration and control panels (right).

# 3 PLANS

## 3.1 *What is planned for the next funding cycle and beyond? How, if at all, is this planning different from the original plan?*

Our gas mixing system is ready to use. We are planning to continue our test beam measurements at Hall-D (CEBAF) and perform measurements with different gas mixtures.

We are planning to test a new prototype with Chromium GEM foils (Cr-GEMTRD proto II) which will be ready by this fall. Cr-GEMTRD prototype will be base on the exact same design as proto I with the only modification being that the standard Copper GEM foils will be replaced by Chromium GEM foil. The two prototypes will be tested this fall in Hall-D at JLab to compare the effect of the GEM Copper electrode on the overall detection efficiency in Xe mixture gas.

Over the next year we will continue to analyze our data and work toward finalizing our results for publication.

## 3.2 *What are critical issues?*

We have identified a several issues and studies which should be pursued in addition to those in our original plans as important steps towards the realization of a new generation of transition radiation

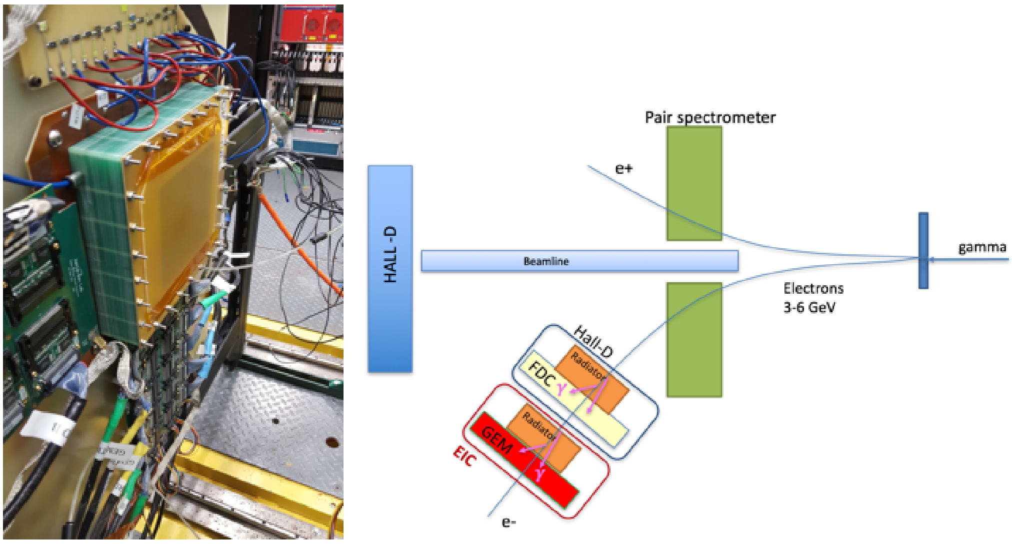



Figure 11: Mechanical support structure and test beam setup at Hall-D (CEBAF). GEM/TRD module was placed behind MW-TRD(FDC) prototype

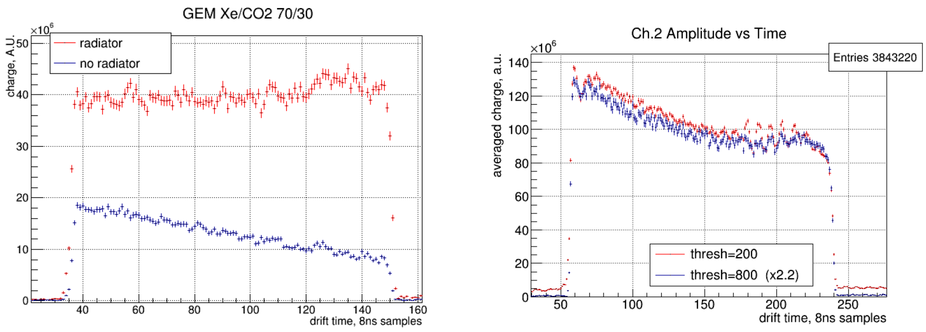



Figure 12: The very first testbeam results with Xe gas mixture with a comparison of an average charge deposition along the drift length with and without radiator (left) and an average charge along the drift time with different thresholds applied for clusters

detectors as a part of the EIC project.

#### 3.2.1 Gas System Improvements

While the gas mixing system is completed and operational there are a few things that we could still benefit by installing. One is to install a gas mixing tube that would provide better turbulence to the mixed gas flow which would create a better gas mixture. This would be based on the unit used in the BNL lab for their gas mixing systems, and consist of a 0.5 inch wide spiraled aluminum strip which is inserted into a 6 inch long copper tube. The second addition would be to install particle filters on the gas source lines. These items would make up our $700 material budget.

An additional piece of equipment that will need to be purchased is a gas analyzer. The gas analyzer will serve two main purposes. The first is that it will allow us to measure the concentrations of the Xe and CO2 gasses that make up the TRD gas. This would allow us to verify and test the performance/accuracy of our mass flow controllers. Additionally the gas analyzer will allow us to begin quantifying and monitoring contaminations within the TRD gas. Such knowledge will help in understanding the detector signal responses and will help if and when a gas recirculation system is installed. Hall D of Jefferson lab is currently in the process of buying a gas analyzer. By splitting the cost with them we would have user rights to the device and be able to use it for our gas mixture verification.

Finally, we will be requesting $3k for travel. Most of this budget would be used for the upcoming JLab test beam where we will install the gas mixing system and test various gas concentrations.

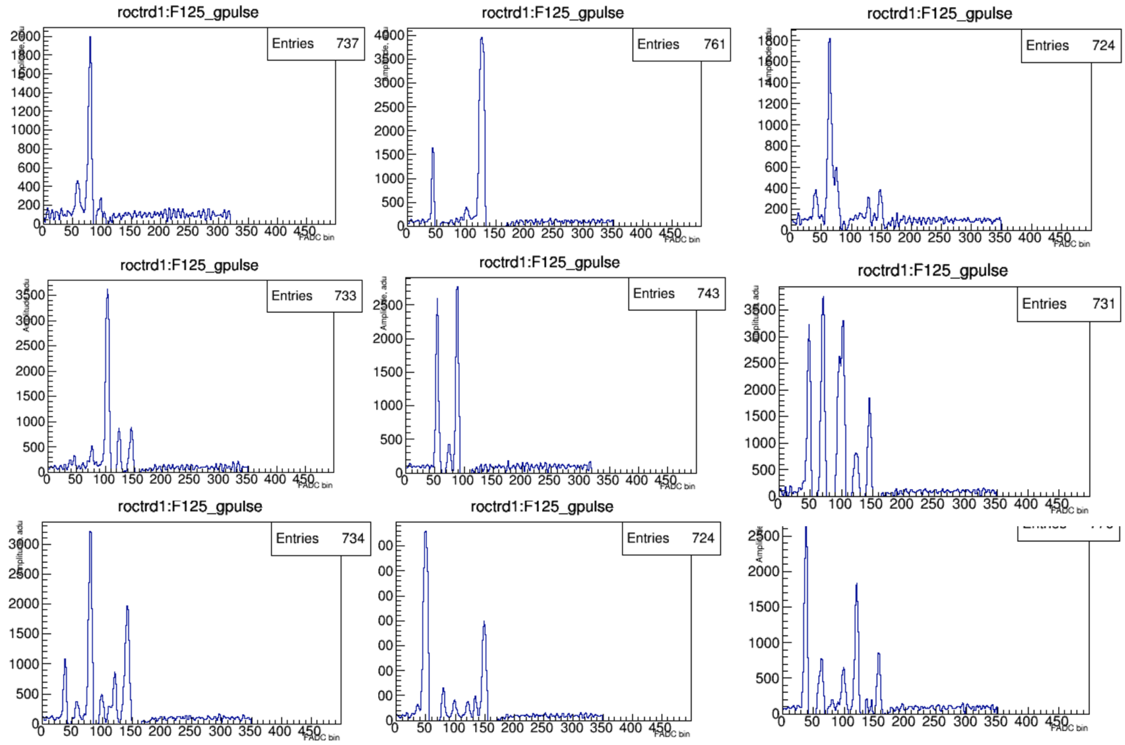


Figure 13: The typical FADC signals from GEMTRD: amplitude vs drift time

### 3.2.2 Tracking analysis

During this year we mostly focused on an optimization of the transition radiation performance of our prototype. Since we are going to use it also as the tracking detector, we would like to evaluate the performance of our prototype as a tracker. Available electronics allowed as to use the drift time information of each individual cluster along the particle trajectory. We are planning to optimize a track finding/fitting algorithms for this type of operation mode. No additional funds would be required to perform this.

### 3.2.3 On-line particle identification

At the moment we are using off-line reconstruction tools for particle identification or electron/hadron rejection. But since we are planning to use advanced technology for a future EIC collider we might need to think about new and advanced ways of data processing. In particular, how could we move a part of an off-line reconstruction software into on-line. And as a part of this commitment we would

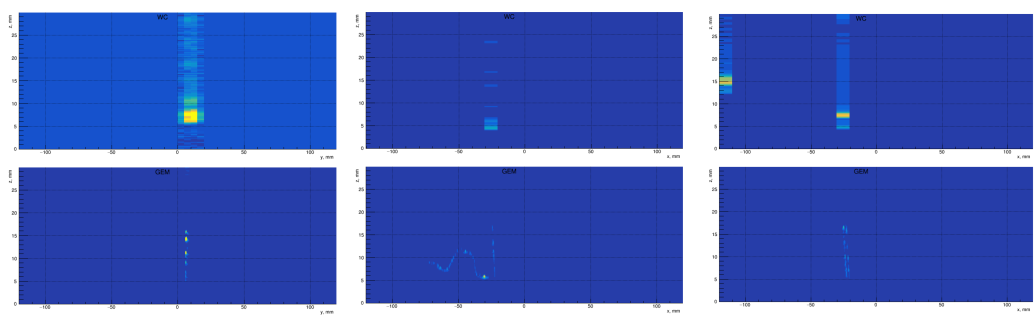


Figure 14: Comparison of a tracking performance: MW-TRD (FDC) (upper plots) and GEM-TRD (lower plots) chambers. The x/y scatter plot shows the deposited ionization (color intensity) on each readout wire (MW) or strip (GEM-TRD) (horizontal) as a function of drift time (vertical)

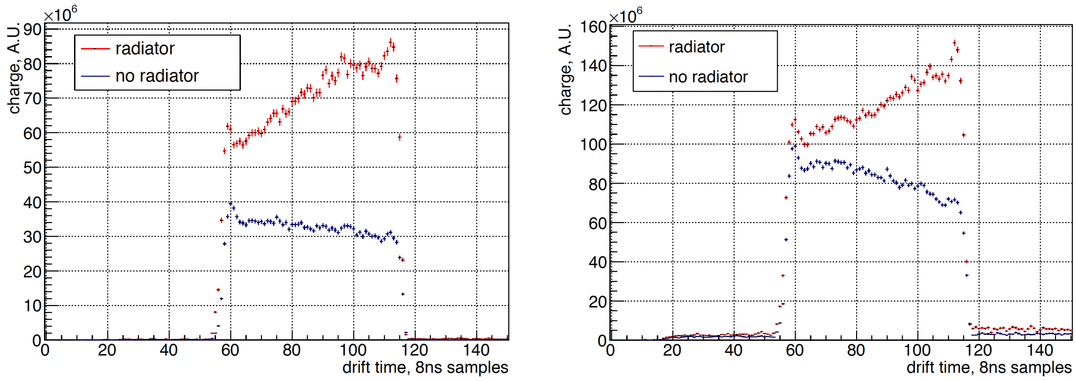



Figure 15: First preliminary results with different radiator materials: fleece (left) and regular foils (right)

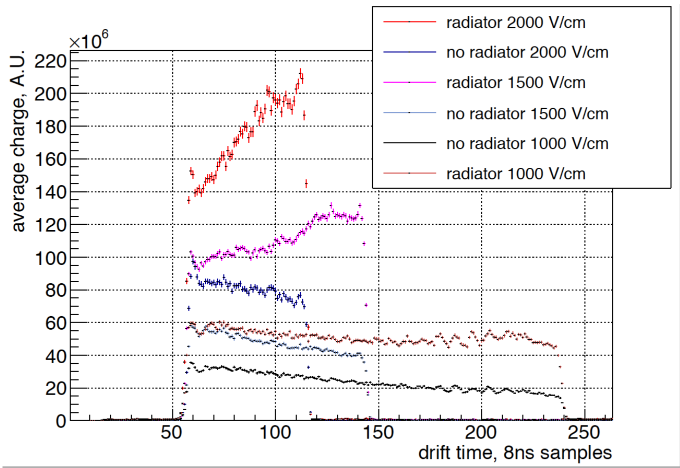



Figure 16: Preliminary results of detector performance with different drift field settings

like to use a FPGA evaluation board (VIRTEX) and adapt our current reconstruction software for on-line usage. We also would like to test our neural-network or likelihood methods, which we are using for electron/hadron separation, on the FPGA.

We would like to request an additional \$10k for FPGA evaluation board with a license.

### 3.2.4 Readout Hardware

A GEM-TRD detector requires special types of readout electronics which would allow to measure individual clusters along the drift volume. Xe-gas, which is needed for an absorption of transition radiation photons, is relatively slow gas. Increasing drift voltages leads to instability of the detector and inability to separate each individual cluster along the particle trail. The available electronics for GEM-types of detectors such as APV25, VMM3, DREAM or SAMPA does not provide necessary coverage or timing resolution.

The FlashADC125 showed a good performance during the test beam of our single GEM-TRD prototype, but the overall price per channel ($>$ 50\$/channel) didn't allowed us to cover a whole sensitive area of our 10x10 cm prototype. The FlashADC125 readout chain was borrowed from JLAB Hall-D for a short period of time for our test.

We would like to collaborate with a readout consortium to work together towards a realization of inexpensive readout chips which would allow us to use it for further GEM-TRD prototypes. An inexpensive readout would allow us to check performance of a GEM-TRD system with multiple layers and would allow us to perform a test with electron and pion beams (for example, at Fermilab or CERN).

### 3.2.5 Radiators Optimization

A test of new materials, which could be used for transition radiation detectors, and a collaboration with material scientists is needed. We need to identify and test promising new radiator materials to optimize the yield of TR-photons.

### 3.2.6 Prototypes

We are following the R&D effort on new technology such as $\mu$RWELL detectors by the eRD6 Tracking consortium and are planning to work in parallel with the consortium toward an optimization of the detector for TRD/Tracking application. The estimated cost for one $\mu$RWELL-TRD prototype would be in the range of $5k.

Additional cost for the development of a customized Gas Volume and a Field Cage for both GEM and $\mu$RWELL prototypes would be required ( $5k), which includes also a technical support (machine shop) and laboratory accessories. A travel support for a JLAB test beam, meetings and conferences ( $5k) will also be needed.

# 4 Additional information

Manpower *Include a list of the existing manpower and what approximate fraction each has spent on the project. If students or postdocs were funded through the R&D, please state where they were located, what fraction of their time they spend on EIC R&D, and who supervised their work.*

None of JLAB, Temple or UVA members are funded by EIC R&D.

Jefferson Lab (JLAB):
F. Barbosa Electrical Engineers 10%
H. Fenker Research Scientist 5 %
S. Furletov Research Scientist 5 %
Y. Furletova Research Scientist 20 %
L. Pentchev Research Scientist 5 %
C. Stanislav Technical Staff 10%
B. Zihlmann Research Scientist 5 %

Temple University :
M. Posik Research Scientist 15 %
B. Surrow Professor 10 %

University of Virginia (UVa):
K. Gnanvo Research Scientist 20 %
N. Liyanage Professor 5 %

The table 1 below summarizes the Temple University budget request for FY19.

Table 1: **Temple University-Gas System** FY19 request.

| | **Request** | **-20%** | **-40%** |
|---|---|---|---|
| Gas supplies | \$700 | \$400 | \$0 |
| Travel | \$3,000 | \$2,000 | \$2,000 |
| Overhead (58.5%) | \$2,165 | \$1,404 | \$1,170 |
| **Total** | **\$5,865** | **\$3,804** | **\$3,170** |

The table 2 below summarizes the Jefferson Lab budget request for FY19.

Table 2: **JLAB: FPGA and Gas Analyzer** FY19 request.

| | **Request** | **-20%** | **-40%** |
|---|---|---|---|
| FPGA evaluation board | \$7,000 | \$0 | \$0 |
| Gas analyzer (% with Hall-D) | \$8,000 (50%) | \$ 5,000 (30%) | \$ 0 |
| Travel | \$5,000 | \$4,000 | \$3,000 |
| Overhead (36.5%) | \$7,300 | \$3,300 | \$1,100 |
| **Total** | **\$27,300** | **\$12,300** | **\$4,100** |

The table 4 below summarizes the University of Virginia budget request for FY19.

Table 3: **UVA prototyping** FY19 request.

| | **Request** | **-20%** | **-40%** |
|---|---|---|---|
| $\mu$RWELL prototype | \$5,000 | \$0 | \$0 |
| Gas/Field cage | \$5,000 | \$ 0 | \$ 0 |
| HV power supply | \$5,000 | \$ 5,000 | \$ 0 |
| Travel | \$5,000 | \$4,000 | \$3,000 |
| Overhead (61.5%) | \$3075 | \$2460 | \$1845 |
| **Total** | **\$23,075** | **\$ 11,460** | **\$4,845** |

The table 4 below summarizes a total budget request for FY19.

Table 4: **A total eRD22** FY19 request.

| | **Request** | **-20%** | **-40%** |
|---|---|---|---|
| JLAB | $27,300 | $12,300 | $4,100 |
| UVA | $23,075 | $ 11,460 | $ 4,845 |
| Temple U | $5,865 | $ 3,804 | $ 3,170 |
| **Total** | **$56,240** | **$ 27,564** | **$12,115** |

### 4.1 External Funding

*Describe what external funding was obtained, if any. The report must clarify what has been accomplished with the EIC R&D funds and what came as a contribution from potential collaborators.*

### 4.2 Publications

*Please provide a list of publications coming out of the R&D effort.*

Not applicable due to early stage of the project.

## 5 Acknowledgments

We would like to thank whole JLAB Hall-D collaboration, in particular E. Chudakov, T. Carstens, for their continues support during a test beam period.